Performance of Structures in the Andaman and Nicobar Islands (India) during the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami

C.V.R. Murty,[a)] M.EERI, Durgesh C. Rai,[a)] M.EERI, Sudhir K. Jain,[a)] M.EERI, Hemant B. Kaushik,[a)] Goutam Mondal,[a)] and Suresh R. Dash[a)]

The damage sustained by buildings and structures in the Andaman and Nicobar islands area was due to earthquake shaking and/or giant tsunami waves. While damage on Little Andaman Island and all the Nicobar Islands was predominantly tsunami-related, damage on islands north of Little Andaman Island was primarily due to earthquake shaking even though tsunami waves and high tides were also a concern. In general, the building stock consists of a large number of traditional and non-engineered structures. Many traditional structures are made of wood, and they performed well under the intensity-VII earthquake shaking sustained along the islands. However, a number of new reinforced concrete (RC) structures suffered severe damage or even collapse. Also, extensive damage occurred to the coastal and harbor structures in the Andaman and Nicobar islands. [DOI: 10.1193/1.2206122]

INTRODUCTION

The M=9.3 earthquake occurred on 26 December 2004 at 06:28:53 A.M. Indian Standard Time (00:58:53 UTC). This created the most devastating tsunami in historic times. In India, about 10,749 people died, and over 5,640 were reported missing; in all, over 2,731,900 people were affected (MHA 2005). The extremely high death toll and damage is attributable primarily to the deadly tsunami waves. However, extensive damage and loss of property in the Andaman and Nicobar (A&N) islands, India, was also due to the seismic shaking and was not attributable to the tsunami waves (Jain et al. 2005). The statistics from the Nicobar Islands indicated severe losses as a percentage of total population; by 18 January 2005, of the total Nicobar Island population of 42,068, about 1,899 were dead, 5,554 were missing, and 18,395 were in the relief camps.

The A&N islands, located southeast of mainland India, are the Indian land masses closest to the earthquake epicenter. These islands are a narrow broken chain of about 572 picturesque islands, islets, and rocks extending along a general north-south direction between 14° N and 6.5° N latitude stretching over a narrow arc of about 800 km in the southeastern part of the Bay of Bengal (Figure 1). Of these, only about 36 islands are

[a)] Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

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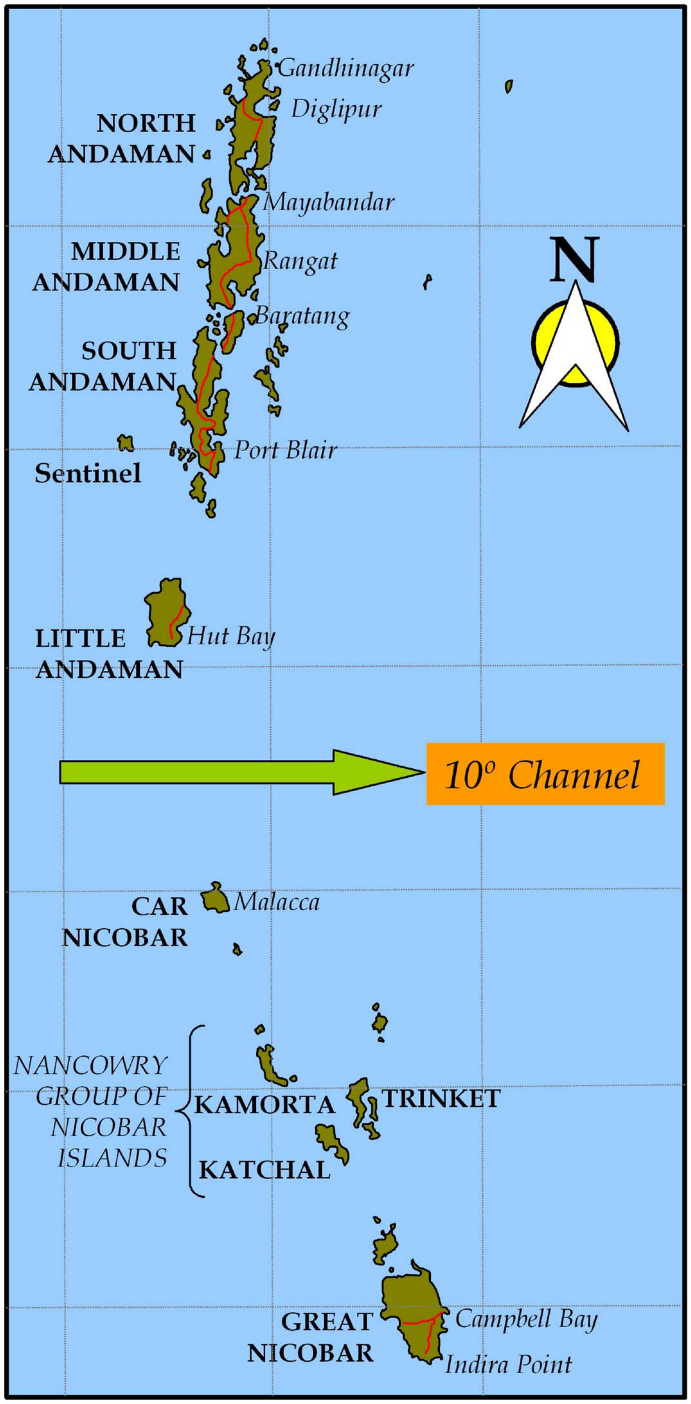


Figure 1. The A&N islands, showing some of the larger islands of the region.

inhabited. The islands are grouped into two sets, with the 10° N latitude international shipping channel standing as the divider; islands above 10° N latitude are called the Andaman Islands, and those below 10° N latitude are called the Nicobar Islands. North, Middle, South, and Little Andaman islands are the most populated among the former islands; and Car Nicobar, Great Nicobar, Katchal, and Kamorta islands are the most populated among the latter. According to the 2001 census, the total population in the A&N islands is about 356,152; about 314,084 people live in the Andaman Islands, and about 42,068 live in the Nicobar Islands.

The 26 December 2004 earthquake occurred along the subduction plate boundary between the Indian plate and the Burma micro plate of the Eurasian plate. Because of the seismic activity in the region, the Indian seismic zone map (Figure 2) has placed the A&N islands in seismic zone V, the most severe one in the country. The location of the main shock was ~200 km SSE of the nearest island (Great Nicobar Island), about 1,000 km SSE from Port Blair, and about 1,800 km SE of Chennai (formerly known as Madras). The main shock and aftershocks suggest that the rupture extended over about 1,300 km of the Sunda and Andaman arc (USGS 2005). The large amount of energy released during this event caused high-intensity ground shaking at several locations along the land masses adjoining this arc. However, a preliminary estimate of the maximum intensity of shaking (on the MSK scale) sustained in India is only about VII along the A&N islands and about V along the east coast of mainland India. The digital strong-motion instrument installed at Port Blair by the India Meteorological Department failed to record the main event. The intensity of ground shaking in Port Blair was placed at VI–VII on the MSK scale (Jain et al. 2005). For shaking intensity VII, the average peak ground acceleration is generally about 0.1 g. Analysis of a collapsed RC bicycle and motor scooter shelter also indicates that the peak ground acceleration in Port Blair during the earthquake was about 0.1 g (Kaushik and Jain 2006).

The distribution of tsunami-induced damage along the A&N islands followed the general trend of more damage in the islands closer to the epicenter and less damage in those farther away. Persons interviewed at Port Blair recall that the water receded before the first wave, and the third wave came with the greatest height and caused maximum devastation. However, persons at locations far south of Port Blair, namely at Hut Bay, Malacca, and Campbell Bay, mention that the water level rose by about 1–2 m from the normal sea level and remained there before the giant wave lashed the entire built environment. Eyewitnesses recall that the tallest of the giant waves was about 5 m high at Campbell Bay (in Great Nicobar Island), about 8 m at Malacca (in Car Nicobar Island) and at Hut Bay (in Little Andaman Island), and about 4.5 m at Port Blair (in South Andaman Island); these wave heights were also corroborated by field measurements by various agencies (DST 2005) (Figure 3). The partial shielding of the coastline at Campbell Bay and significant shielding of Port Blair and Campbell Bay by the steep mountainous outcrops from the direct tsunami waves originating from Sumatra may have contributed to the reduced wave heights at these locations. However, the open terrain along the eastern coast of the islands at Malacca and Hut Bay is seen as a reason for the large height of the tsunami waves.

The field investigations covered the North, Middle, South, and Little Andaman is-

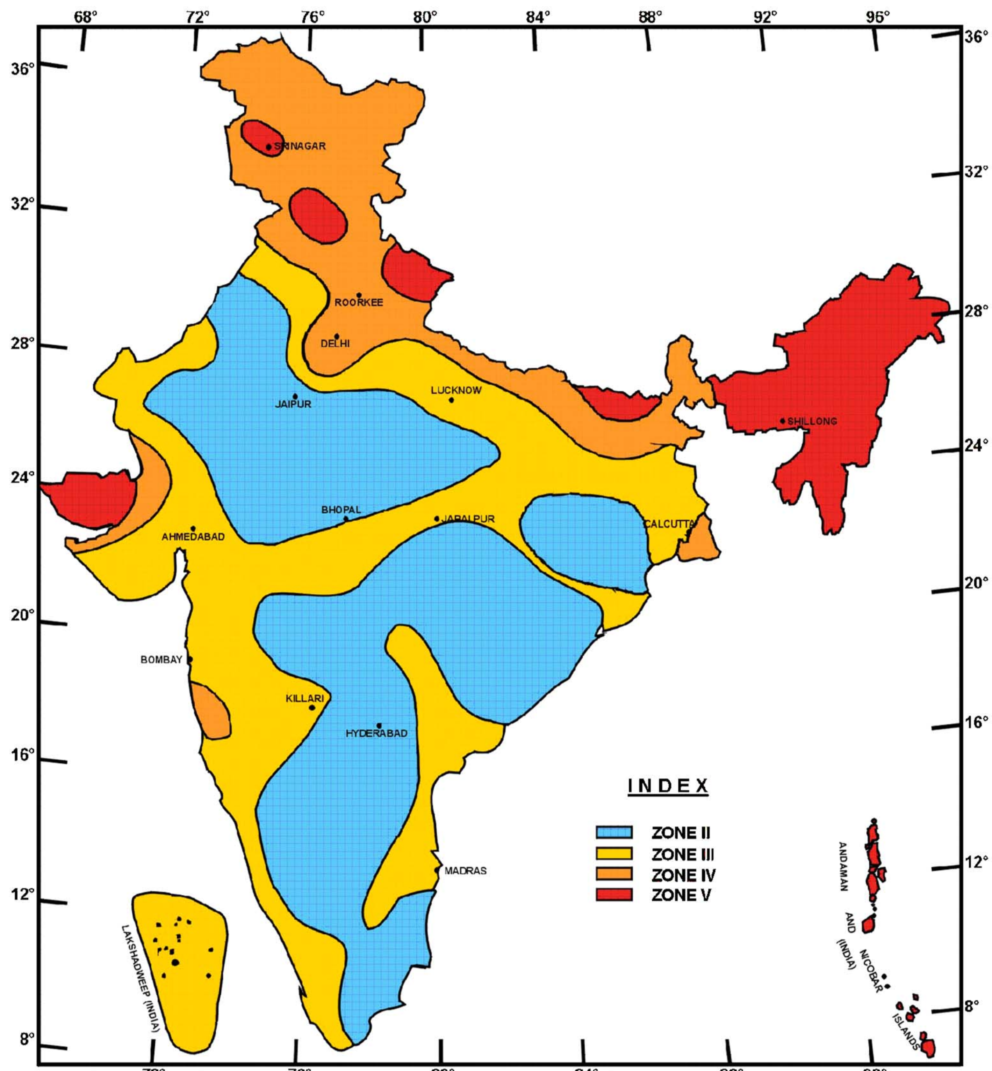


Figure 2. The A&N islands are in the most severe seismic zone, and the east coast of India is in the moderate-to-low seismic zone (source: BIS 2002).

lands and the Car and Great Nicobar islands (Figure 1). The damage sustained by buildings and structures in the A&N area is due to both the earthquake shaking and the giant tsunami waves. It was difficult to identify the primary cause of damage in some instances, but input from local residents suggested the origin of damage. Hence the two types of damage are discussed separately, as those due to earthquake ground shaking alone and those due to the tsunami waves alone.

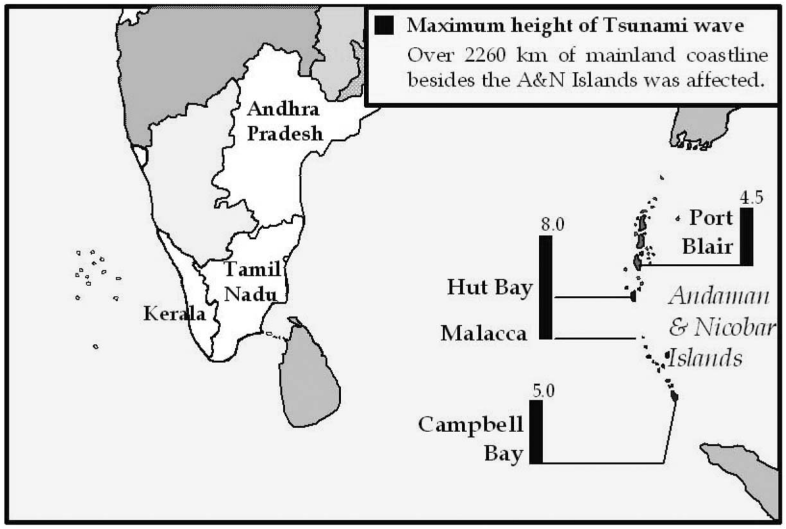


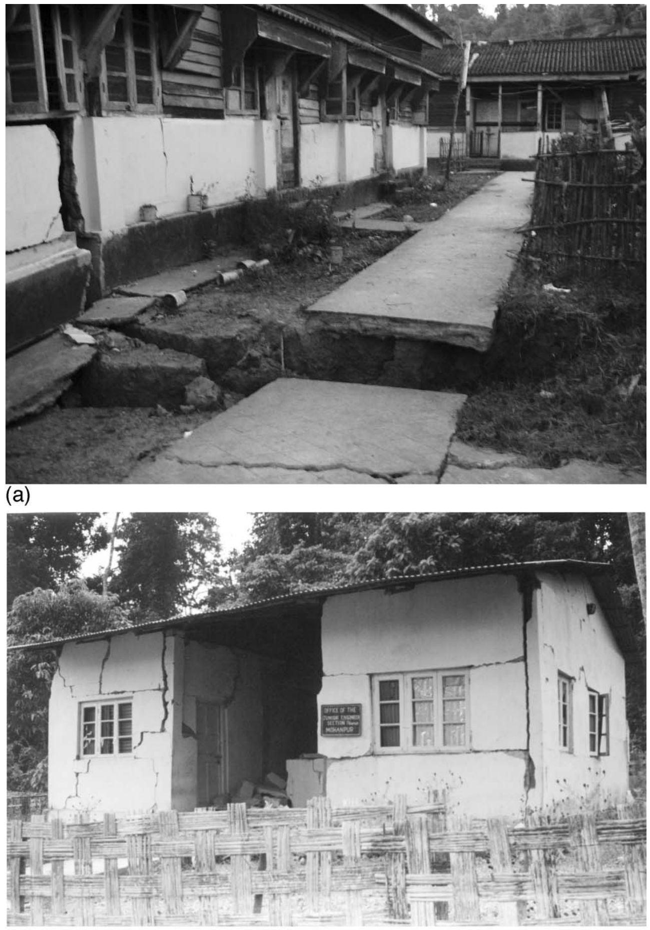
Figure 3. Maximum tsunami wave heights at various locations in the A&N islands. The vertical bar indicates the amplitude of wave height, and the number on it indicates the value in meters.

EARTHQUAKE SHAKING-RELATED EFFECTS

GROUND DEFORMATION AND LIQUEFACTION

The shaking intensity of VI–VII in the A&N islands is low for significant liquefaction to be expected in these islands. However, even with low-intensity shaking, the long duration of shaking coupled with the shallow depth of the water table in many coastal areas may have contributed to occurrences of liquefaction. Evidence of liquefaction was noted in the South, Middle, and North Andaman islands. However, no signs of liquefaction were available on the ground surface in Little Andaman Island and the three Nicobar Islands visited—namely Hut Bay, Malacca, and Campbell Bay—and even if there once had been such signs, the giant tsunami waves carried away large amounts of debris and topsoil from the coastline and thus carried away evidence of any liquefaction. Also, tsunami waves deposited layers of fine soil on the land. An older mud volcano became active again after the shaking at Baratang in Middle Andaman Island, and several new small mud volcanoes also erupted, along with the occurrence of large ground deformation.

Amplification of ground motion coupled with liquefaction and lateral spreading of alluvial soil caused severe damage to the colony. Liquefaction in the form of sand boils was observed at different places. The ground shaking was so strong that people were not able to stand during the earthquake. Lateral spreading and other liquefaction-related phenomena were responsible for extensive damage to residential buildings (Figure 4) and health care facilities in the low-lying areas, especially in the vicinity of water bodies,



(a)

(b)

Figure 4. Damage to residential buildings: (a) severe damage to houses in the government residential area in Nimbudera village in Middle Andaman Island, where large ground motion and liquefaction were noted; and (b) at Mohanpur village in North Andaman Island, a single-story masonry building—despite having a light roof—sustained severe damage due to the lack of any earthquake-resistant features; the area around the building seems to have suffered significant amplification of the ground motion (photos: G. Mondal).

at several places in the northern Andaman Islands. At Mohanpur village, which sustained large ground amplification, thatch dwellings on wooden posts collapsed because of insufficient tying between the rafters and posts.

The excessive liquefaction, severe ground amplification, and occurrence of mud volcanoes need to be understood in light of the global plate tectonics of this earthquake. Detailed investigations along with collateral evidence of plate tectonics and GPS readings may provide further clarity.

Figure 5. Settlement of RC buildings at Bamboo Flat near Port Blair (photo: H. Kaushik).

Most of the buildings in Port Blair are constructed on sloping ground, because of significant variation in the ground level on the islands. Ground sliding along the slope up to about 50–75 mm was observed at the plinth level of several buildings at Aberdeen Market and Dilanipur. The three-story RC police station building at Aberdeen Market, constructed on sloping ground, moved laterally by about 75 mm. A lateral movement of about 50 mm at the plinth level of a three-story RC building at Dilanipur was observed during the visit.

Settlement of buildings was observed at several locations in Port Blair, possibly due to foundation failure, erosion/settlement of underlying soil due to inundation of the region by tsunami waves, and liquefaction. In most cases, buildings near the sea settled in the earthquake, and signs of liquefaction, if any, were washed away when the tsunami struck. Two RC buildings and several shops in the shopping complex in Bamboo Flat near Port Blair settled, possibly due to liquefaction (Figure 5). Several buildings in the harbor area in Port Blair settled due to structural failure of some of the foundation piles. Figure 6a shows settlement of piles in the passenger terminal building at Haddo Wharf. Figure 6b shows severe damage at the junction of an RC pile and its pile cap supporting an RC building used for storage at Haddo Wharf.

BUILDINGS

While damage to buildings and structures in Little Andaman Island and all the Nicobar Islands was predominantly tsunami-related, damage in islands north of Little Andaman Island was primarily due to earthquake shaking. In general, the building stock consists of a large number of traditional and non-engineered structures. Many traditional

(a)

(b)

Figure 6. (a) Foundation (RC piles) settlement/failure resulted in settlement of the passenger terminal building at Haddo Wharf. (b) Dislocation of a pile cap in an RC storage building at Haddo Wharf (photos: H. Kaushik).

structures are made of wood, and they performed well under the intensity-VII earthquake shaking. However, a number of newly constructed RC structures suffered severe damage or even collapse due to shaking (Figure 7).

The wood houses have a number of features that may have helped to reduce the damage during earthquake shaking. These features include light tin sheet roofing, masonry walls up to only the plinth level, and a relatively simple structural configuration (Figure 8a). In some instances, the connection between the wood frame and the masonry plinth

Figure 7. Buildings in Port Blair that were subjected to similar ground shaking intensity performed differently: a three-story RC-frame building collapsed in a brittle manner (photo: S. Jain).

was observed to be poorly maintained (Figure 8b). However, even these structures performed well in contrast to the brittle unreinforced masonry buildings.

The A&N islands had several masonry buildings for residential and storage purposes, hospitals, schools, churches, jails, and so on before the severe earthquake of 26 June 1941 (magnitude 7.7). The famous masonry structure of the cellular jail was constructed in Port Blair over a period of ten years from 1896 to 1906 using solid brick masonry. The cellular jail was a huge structure, with a five-story central controlling tower and seven three-story wings containing 696 cells emanating from the central tower. The masonry used in the construction of the cellular jail was of a very high quality prevalent in India at that time (Figure 9).

Several masonry structures—including a part of the cellular jail—were damaged during the 1941 earthquake, and after independence in 1947 the Indian government declared the remaining three wings of the cellular jail a heritage structure. At present, only a few masonry structures are left in Port Blair, and these performed well during the shaking.

The traditional structures built by the native islanders also demonstrate an understanding of the effects of earthquake shaking on buildings. The huts made by the Sompien tribe have a regular configuration and light mass (Figure 10). The 2-m-diameter circular structure on eight axisymmetrically placed 75-mm-diameter posts is built at an elevation of 1.4 m. The use of local material such as bamboo and thatch makes these structures the first choice for housing among the native population. Unfortunately, for many reasons, more recent migrants to the islands have chosen not to adopt these materials. These reasons include the prohibition against the use of wood in construction and

(a)

(b)

Figure 8. (a) In the Port Blair area and Rangat, wooden buildings with simple configurations performed well during ground shaking. (b) Some buildings with poor maintenance of the joinery between the wood frame and masonry plinth also performed well (photos: D. Rai).

Figure 9. Undamaged three-story masonry structure of the cellular jail (photo: S. Jain).

the migrants' desire to have a concrete roof for protection against all weather conditions. The migrants usually choose to build masonry or RC houses directly on the ground that are rectangular in plan.

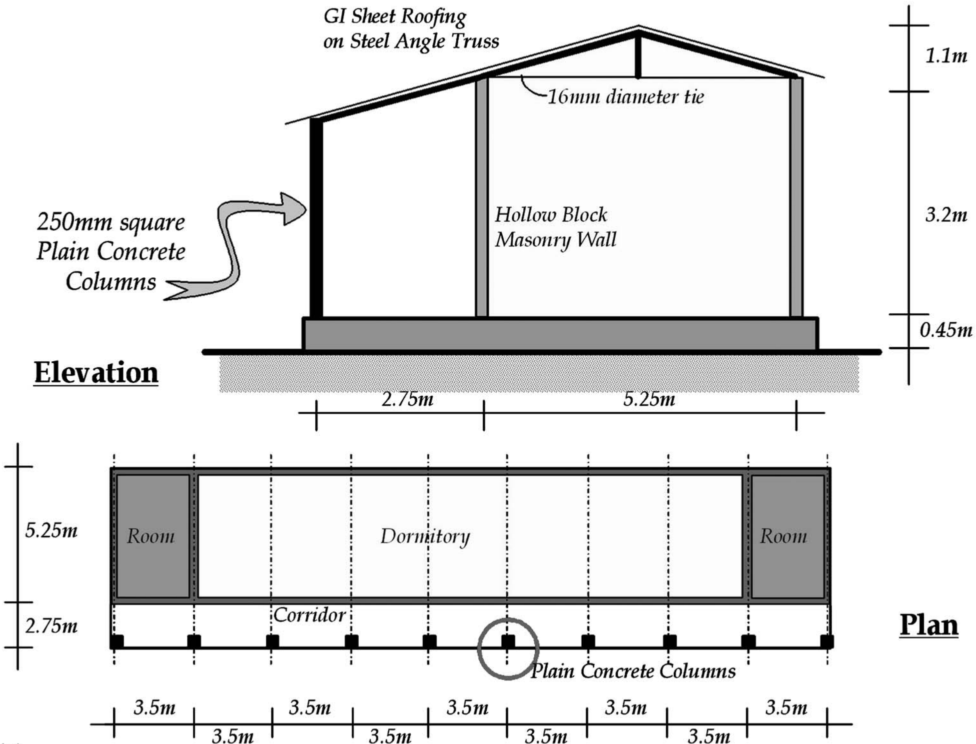
The Army land area in Great Nicobar Island has a number of single-story barracks

Figure 10. Typical hut built by the Sompien tribe living in the islands. This is a prototype hut built in the Army land area in Campbell Bay in Great Nicobar Island (photo: C. Murty).

built as load-bearing masonry during 1982–83 by the Border Roads Organization (BRO). The typical barracks unit is 31.5 m long and 5.25 m wide. The ends have 3.5-m-wide rooms, but the rest of the building does not have cross walls. The superstructure is built of precast hollow cement blocks (twin cell with a 25-mm thick wall, 390 mm long × 190 mm wide × 190 mm high), while the foundation is in precast solid cement blocks. The veranda has 250-mm square plain concrete columns. The choice of plain concrete columns was made by the BRO to reduce the use of wood; this is different from the usual choice of wooden columns in the traditional structures of similar configuration in the island area. The roof consists of corrugated galvanized iron (GI) sheets supported on a steel angle truss. The bottom chord of the truss over the room is a 16-mm-diameter bar running across the room (Figure 11a). However, there is no such truss over the veranda area; the rafter rests directly on these plain concrete columns without any horizontal ties. A continuous lintel band is provided all around, but no vertical reinforcement is provided at wall corners and openings. However, two HYSD bars of 8 mm diameter are provided at every fourth course (~800 mm centers) in the mortar bed joints. In general, these structures sustained horizontal cracks in the wall between the eave level and the lintel band along the full length of the building. Also, the plain concrete columns in the veranda area sustained cracks at the top and bottom. In one such building, such a column even collapsed (Figure 11b). Similar buildings with a larger number of cross walls performed better.

Often, in private masonry dwellings with load-bearing walls and a light roof truss made of steel pipes or timber, walls were not tied together to create the necessary box action required for lateral resistance in masonry construction. No positive connection was provided between the walls and the truss members resting on them; masonry walls collapsed out-of-plane during large movement of the flexible roof that consists of poorly jointed wooden truss members. Similar damage was observed at a much larger scale in most of the school buildings, wherein the long partition walls separating two classrooms have either been badly damaged or have fallen to the ground due to out-of-plane instability of these slender walls (Figure 12). In the three-story RC Mohunpura school building at Port Blair, long masonry infill walls tilted out-of-plane because of poor masonry and because of inadequate and loose joints between the RC frame and masonry walls.

Private structures that did not account for seismic forces in their design suffered collapses. A few RC buildings near Port Blair that had been built with nominal engineering inputs collapsed; Figure 13 shows an example. Most of the recently constructed multistory buildings were a mimic of the nonseismic construction being practiced in mainland India, and they performed poorly (Figure 14). Even the structures designed and built by the government fared no better. For instance, the passenger terminal building at Haddo Wharf in Port Blair is a major facility built only about 5 years ago. Since the area lies in seismic zone V, the ductile detailing is mandatory as per BIS code IS:13920 (BIS 1993). Unfortunately, the design does not follow the ductility provisions. A part of the building toward the sea rests on piles, while the rest is founded on filled-up soil. The building suffered irreparable damage, with some of its columns away from the seaside



(a)

(b)

Figure 11. Military barracks in the Army land area at Campbell Bay in Great Nicobar Island: (a) typical dimensions of a unit, (b) collapse of a plain concrete corridor column (photo: S. Dash).

Figure 12. Slender masonry walls became dislodged because of out-of-plane instability and poor connection or no connection to the surrounding structural elements at the senior secondary school building in Adazigin, Middle Andaman Island (photo: D. Rai).

collapsing (Figure 15). In general, under earthquake shaking, RC-frame structures suffered various kinds of damage ranging from frame-infill separation and hinging at the ends of frame members to complete structural collapse.

Type-design RC structures are built in the A&N islands for community facilities, such as the *panchayat bhavan*, and for government office buildings; these type-designs were developed in-house by the Andaman Public Works Department (APWD). Such structures in the region do not follow the earthquake-resistant construction practices laid out in the Indian standards. These kinds of structures were severely damaged during shaking intensity VII manifested in the islands. For instance, the *panchayat bhavan* building in Nabagram, North Andaman Island, sustained severe cracking to the infills and to the brittle RC columns in the open first story (Figure 16). This building was also affected by a smaller North Andaman earthquake (at Diglipur) in 2002 (Rai and Murty 2003, 2005); only cosmetic repairs were undertaken after that earthquake. Other such buildings were damaged during the 2002 North Andaman earthquake, cosmetic repairs were undertaken after that, and the buildings were once again damaged in the 2004 earthquake; these include the Turtle Resort building in North Andaman Island (Figure 17), and the Mahatma Gandhi Polytechnic building and post office building in Mayabandar in Middle Andaman Island, all built by the government.

Buildings with stilts are becoming common in the islands. A number of government structures are built with this configuration; in many cases, the RC column sizes are as small as 150–230 mm. Earthquakes across the country and the world have shown the vulnerability of such systems. In some instances, such buildings may have performed satisfactorily, apparently because of the inadvertent presence of a number of other elements that contributed to the strength and stiffness of the story with the stilts. The dam-

(a)

(b)

Figure 13. An RC-frame residential building that had been built on stilts near Port Blair collapsed because of severe seismic shaking in the Bamboo Flat area (photos: S. Jain).

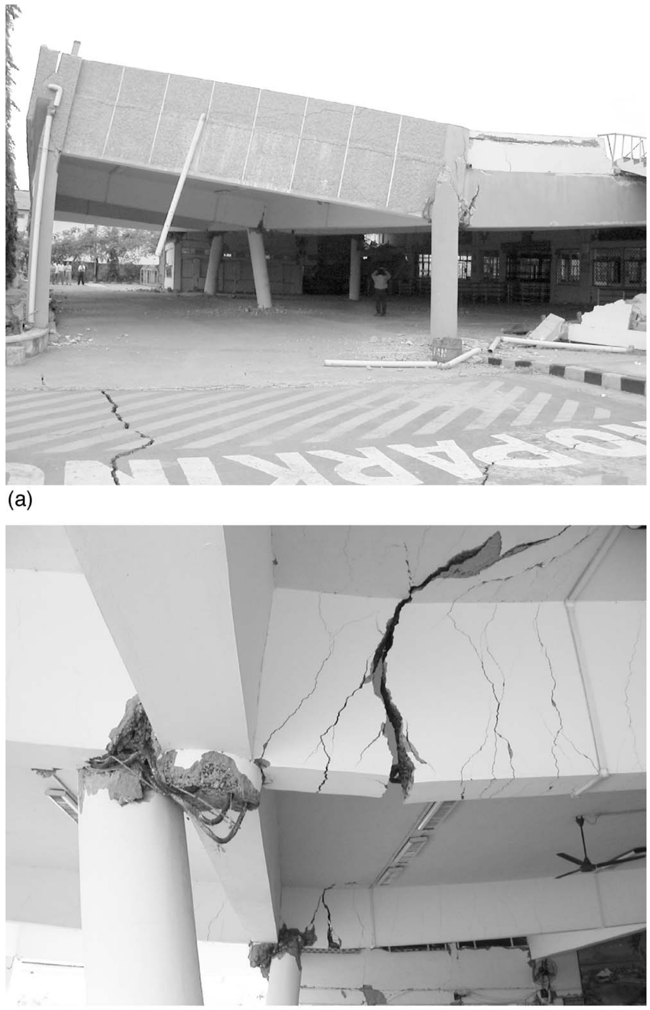
age recorded in the 2004 earthquake also shows the same trend. When the frame is made of such small columns but is infilled with masonry walls having a large number of fenestrations, considerable damage was observed in the masonry adjoining the columns. In the recently completed construction of the two-story RC-frame *panchayat bhavan* building at Urmilapur near Rangat in Middle Andaman Island, cracks developed in at least 14 columns in the first story at the location of the construction joint about 2.1 m above ground level and about 0.6 m below the second floor.

(a)

(b)

Figure 14. (a) Collapse of an open-story RC house at Rampur, near Mayabandar (photo: D. Rai). (b) Collapse of the RC bare frame of a three-story building under construction at Rangat, Middle Andaman Island (photo: G. Mondal).

In Little Andaman, Car Nicobar, and Great Nicobar islands, the maximum intensity of shaking observed was only about VI on the MSK scale, as evidenced by damage to buildings on high ground or well away from the shore. For instance, the two-story government senior secondary school building at Hut Bay in Little Andaman Island has an F-shaped plan but a simple structural system (an RC frame with infill masonry walls at regular spacing in the short direction). This building is situated about 2 km from the shore, and shaking caused only frame-infill separation. This building also was flooded



(a)

(b)

Figure 15. (a) The passenger terminal building at Haddo Wharf collapsed due to the failure of brittle RC columns (photo: S. Jain). (b) Failure of RC columns and large flexural cracks in RC beams (photo: H. Kaushik).

up to about 1.5 m above the finished floor level but did not sustain any structural damage from this water level. There are also other instances of shaking-induced damage to poorly designed and/or poorly built buildings even when they were located well away from the coast. For instance, the two-story telephone exchange building with a highly irregular configuration just opposite the aforementioned school building in Hut Bay sustained severe damage to both the structural as well as nonstructural elements (Figure 18). The main cause is considered to be the short-column-effect damage that the venti-

Figure 16. The Nabagram *panchayat bhavan* building was shaken by two earthquakes—on 14 September 2002 and 26 December 2004. Severe cracking and damage were observed in the soft first-story columns, and columns in the first story that were primarily damaged in the 2002 earthquake because of "missing" ties were now more severely damaged in the 2004 earthquake, even though they had apparently been "retrofitted" (photo: D. Rai).

lators caused to the top portion of the columns adjacent to them in the first story; this building was also flooded by about 2 m from the ground level due to the tsunami wave runup, which damaged the nonstructural elements and components in the first story. The short-column effect is a very common problem noticed in many structures.

In general, these structures do not follow seismic design practices, even though the requisite seismic design codes exist in India. This is exemplified by the collapse of the single-story bicycle and motor scooter shelter because of the earthquake ground motion. The shelter's stiff roof resting on very slender vertical columns indicates the lack of basic concepts like strong column/weak beam in the design practice (Figure 19). An approximate analysis of this collapsed RC shelter indicates that the peak ground acceleration in Port Blair during the earthquake was about 0.1 g (Kaushik and Jain 2006). Also, the construction practices in such structures lack quality control, as demonstrated by the incomplete hook lengths of the lateral ties in beams even though they are closely spaced (Figure 20a) and the use of 90° hooks in the beam and column ties (Figure 20b).

Pounding Damage

Because of the scarcity of open space, buildings in Port Blair are generally constructed very close to each other without a sufficient gap for large lateral deformations during strong ground shaking. Several buildings in the Bamboo Flat shopping complex (Figure 21) suffered substantial cracking and damage at the floor level in slabs, and in columns due to pounding with the adjacent buildings. The L-shaped three-story RC school building at Mohanpura in Port Blair, constructed in stages between 1986 and 1989, was damaged at the expansion joints in the building between different blocks.

(a)

(b)

Figure 17. A two-story RC-frame Turtle Resort building in Shibpur, south of Diglipur, with an irregular structural configuration was also damaged during the 14 September 2002 $M_L=6.0$ earthquake in North Andaman Island, but only cosmetic repairs were undertaken after that event. This building then sustained damage during the 26 December 2004 earthquake in the same places. (a) Bottom of an upper-story column, and (b) top of a lower-story column (photos: D. Rai).

Figure 18. The BSNL telephone exchange building on higher ground at Hut Bay in Little Andaman Island was severely damaged due to earthquake shaking—it was twisted about the vertical axis during the shaking and sustained severe irreparable damage in its structural members. The structure was also flooded by the tsunami runup, and severe loss was sustained in nonstructural elements and contents (photo: C. Murty).

Figure 19. Collapse of a 2-m-high shelter for bicycles and motor scooters near the Port Management Board office complex in Port Blair (photo: S. Jain).

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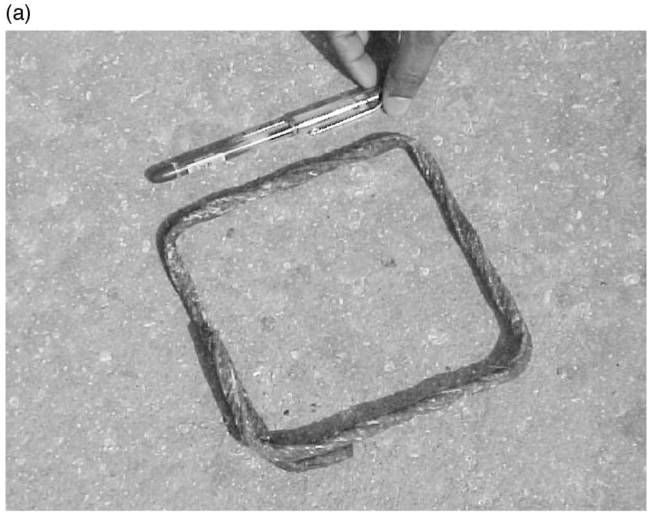


(b)

Figure 20. (a) The RC-frame construction under way for the new office complex near the marine jetty in Port Blair indicates poor compliance with the seismic requirements (photo: S. Jain). (b) Use of 90° hooks in RC-frame construction in Little Andaman Island (photo: C. Murty).

Damage to Nonstructural Elements

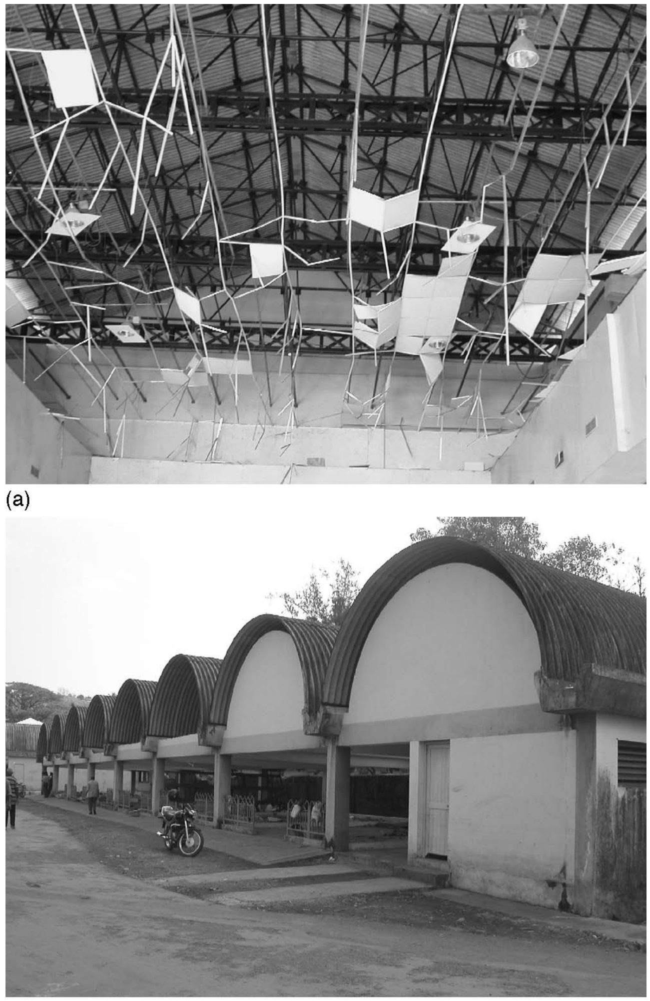
In the old dry dock in the marine jetty dry dock complex in Port Blair, several instances of nonstructural damage due to earthquake shaking were observed. The false ceiling of a fiberglass boat shed collapsed completely, disrupting the already-affected work in the shed (Figure 22a). Laterally unsupported masonry walls in shell structures used as a storage area in the dry dock complex collapsed due to the absence of any confining elements (Figure 22b).

Figure 21. Pounding occurred between closely constructed buildings in and around Port Blair. These buildings are in the Bamboo Flat shopping complex (photo: S. Jain).

Aircraft Hangar Structures

The steel tubular frame structure of the helicopter hangar at Car Nicobar Airport is 60 m $\times$ 60 m in plan, with a gable roof 14 m tall at the eave level and 21.5 m at the crown. Eleven tubular trusses at 6-m spacing run along the transverse direction of the hangar. Each tubular truss has a 1.5 m $\times$ 1.7 m rectangular plan configuration (1.7 m along the transverse direction of the hangar) with 160-mm-diameter pipes as corner elements, 100-mm-diameter pipes as inclined braces along the transverse direction, and 80-mm pipes as horizontal braces in the longitudinal direction of the truss. The 11 tubular gable trusses are connected to each other through steel pipes running in the longitudinal direction, except in the end bays, where three X-braces are provided over the 14-m vertical height between the end two trusses (Figure 23a). The braces are made by welding the two pipes directly to each other without any gusset plate arrangement; the fillet welding was performed along the curved interface surface. During the earthquake, the end X-braces failed along these curved weld lines (Figure 23b). The third-story braces even fell down to the ground.

The hangar structure at Port Blair Airport, known as the INS Utkarsh Complex, also suffered slight damage due to ground shaking. The steel-frame structure, constructed in 1986, was 50 m $\times$ 50 m in plan, with a roof truss 10 m tall at the eave level and 14 m at the crown (Figure 24a). Many of the braces in the steel columns, which were made of 15-mm square bars, were found to be buckled (Figure 24b). Several of the gusset plates connecting inclined brace members between adjacent columns buckled because of non-concurrent members meeting at the plate (Figure 24c). Severe corrosion was observed at the junction of the base plate and columns (Figure 24d).



(a)

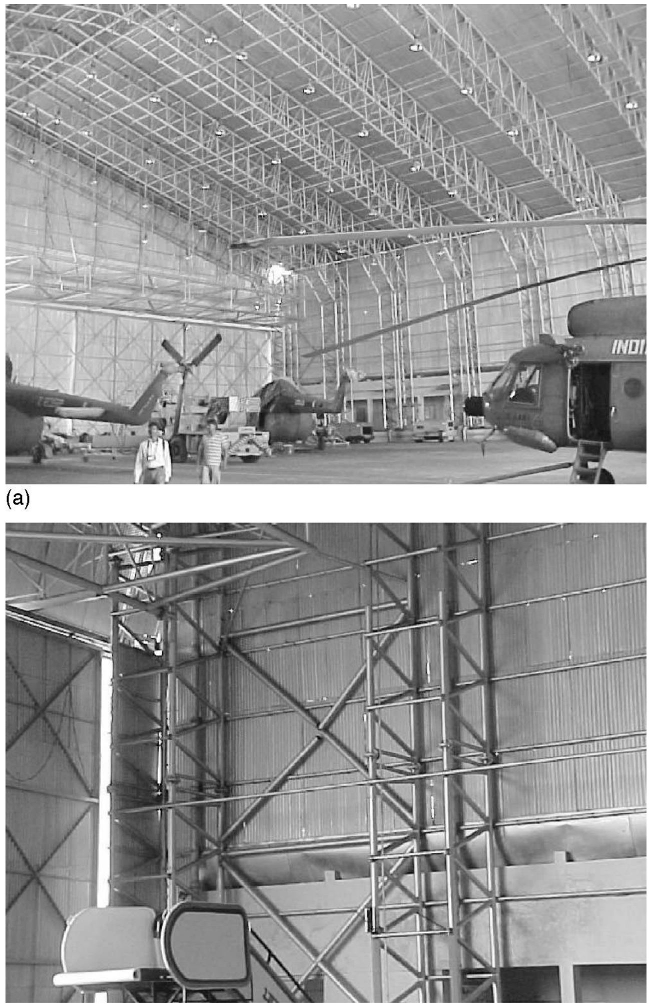
(b)

Figure 22. (a) Collapsed false ceiling of the fiberglass boat shed in the marine jetty dry dock complex (photo: S. Jain). (b) Out-of-plane collapse of nonstructural masonry walls in a storage structure at the dry dock (photo: H. Kaushik).

TSUNAMI-RELATED EFFECTS

BUILDING DAMAGE

The giant tsunami waves caused severe destruction in the coastal areas of the southern islands. A large number of buildings constructed right on the coast were washed away. Complete devastation of the military residential colony south of Malacca on the east coast of Car Nicobar Island and of the built environment on the east coast of Hut Bay in Little Andaman Island was observed. The non-engineered (Figure 25a) as well as



(a) (b)

Figure 23. Helicopter hangar at Car Nicobar Airport: (a) tubular truss configuration, and (b) weld failure at the X-braces in the end panels (photos: C. Murty).

engineered RC structures performed poorly during the tsunami. However, an occasional well-designed RC structure can be seen standing even in the tsunami-devastated areas (Figure 25b). In general, flat lands adjoining the coast were the hardest hit. Structures that thronged by the shore were subjected to positive water pressure when the giant wave arrived and suction pressure when the wave receded. This pressure loading due to the tsunami was rarely resisted by a building on the ocean front without any damage. In the best cases, the frame of the RC-frame infilled building was intact, while the infills were pushed out of plane (Figure 26a); presumably, the RC frames in these buildings were well designed and constructed. A little further from the coast, other RC-frame buildings

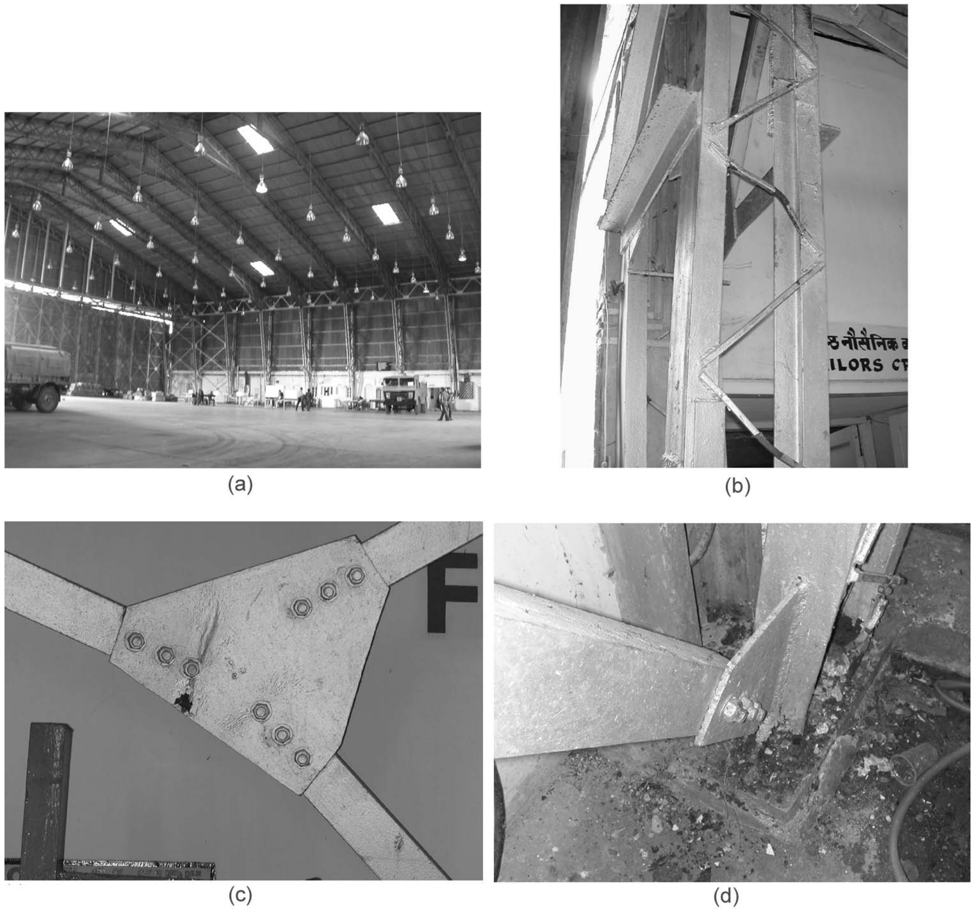


Figure 24. INS hangar at Port Blair Airport: (a) truss configuration, (b) buckling of braces in steel columns (photos: H. Kaushik), (c) buckling of gusset plates connecting nonconcurrent braces between adjacent columns, and (d) severe corrosion at the junction of the base plate and column at the ground level (photos: S. Jain).

with masonry infills sustained severe damage only in the first story, owing to the punching out of the infills by the large lateral pressure of the tsunami (Figure 26b). In cases where a number of buildings were built in a row normal to the coast, the giant waves destroyed the structures toward the coast; buildings in the rear of such a row managed to survive because they were shielded from the giant wave by buildings in the front (Figure 27). In all, the number of surviving buildings at the shoreline of islands like Little Andaman and Car Nicobar is only a very small fraction of the total number of houses. Many structures that are seemingly standing are severely damaged or almost destroyed, with their basic structural safety in question due to scouring of the soil from underneath the foundation (Figure 28).

(a)

(b)

Figure 25. (a) General destruction of non-engineered structures that resisted the giant tsunami waves in the fishermen's colony (Machchi Dera area) at Hut Bay in Little Andaman Island (photo: C. Murty). (b) Three-story RC-frame building with many masonry infill interior walls located right at the shore adjacent to the fishermen's colony at Hut Bay in Little Andaman Island; this building sustained no apparent structural damage despite lateral pressure from the tsunami (photo: S. Dash).

(a)

(b)

Figure 26. (a) Two-story RC-frame shorefront building with masonry infills in the military residential area in Car Nicobar Island. It was inundated but resisted the wave effects. Even though the building frame survived the wave effects, the great pressure sucked away the masonry infills, the occupants, and the contents. (b) Two-story RC-frame building with masonry infills about 300 m from the shore at Hut Bay in Little Andaman Island. The first story of this Andaman & Lakshadweep Harbour Works residential facility was submerged. It sustained severe structural damage in the first story due to lateral pressure of the tsunami and could not save the lives of people in the lower story (photos: C. Murty).

(a)

(b)

Figure 27. Military residential area in Car Nicobar Island: (a) buildings in a row normal to the shore show progressively increasing damage toward the coast, and (b) in large shorefront structures, the seaward section was severely damaged while the back side was relatively undamaged (photos: S. Dash).

Figure 28. These buildings at the Air Force Colony in Car Nicobar Island are apparently standing after the tsunami, but their foundations have been scoured away (photos: C. Murty).

Of all the islands that were affected, Katchal and Kamorta islands suffered the most. But the most publicized one was Car Nicobar Island, which had the Air Force Station and its beautiful residential colony at the seashore. The ground level at the colony is only slightly above sea level. The colony buildings were first shaken by the ground motion, and then, due to their proximity to the sea and low ground level, lashed by the giant tsunami waves. Many buildings were block masonry structures on strip footing; such buildings suffered damage due to ground shaking and liquefaction, and the final blow was given by the tsunami waves. Most of the buildings suffered total collapse, and many have been washed away. The debris and household items strewn all around present a de-

Figure 29. This RC-frame MES inspection bungalow now stands in waters at the Air Force Colony south of Malacca on the east coast of Car Nicobar Island (photo: C. Murty).

pressing view and tell the story of the brute force of the waves. The Military Engineering Service (MES) inspection bungalow at the Air Force Colony on this island was situated about 100 m from the seashore. Due to the eastward tilting of the Burma microplate on which the A&N islands are located and the subsidence of the eastern coast of the A&N islands, the shore at the Air Force Colony on Car Nicobar Island subsided by about 1.5 m. Owing to this, the water level of the sea in this area was reported to have risen by about 1.5 m after the earthquake. As a consequence of this ground shaking, subsidence, and tsunami, this building sustained severe structural damage and is in a state of incipient collapse, with the seawater lashing at its column footings (Figure 29).

On the other hand, in the Andaman Islands, while tsunami-induced damage to the contents of buildings was significant, the fury of the waves was less and caused less tsunami-induced damage to the structure of the buildings themselves. For instance, in the Bamboo Flat area near Port Blair in South Andaman Island, the street-front shops were inundated because of land subsidence. The steel shutters of the shops were damaged, and the drainage covers were displaced (Figure 30). In some other buildings in the same region, the boundary walls collapsed. In the old dry dock in the marine jetty dry dock complex in Port Blair, the water pressure caused out-of-plane collapse of the masonry infill walls (Figure 31).

HOSPITALS

Because of the tsunami, civic administrators need to consider relocating the limited critical infrastructure, like hospitals, at higher elevations. At Hut Bay in Little Andaman Island, the hospital was about 500 m from the coast and sustained partial collapse during earthquake shaking and inundation (Figure 32). The partial collapse is attributable to the rusted structural steel building system that is many decades old; its main structural

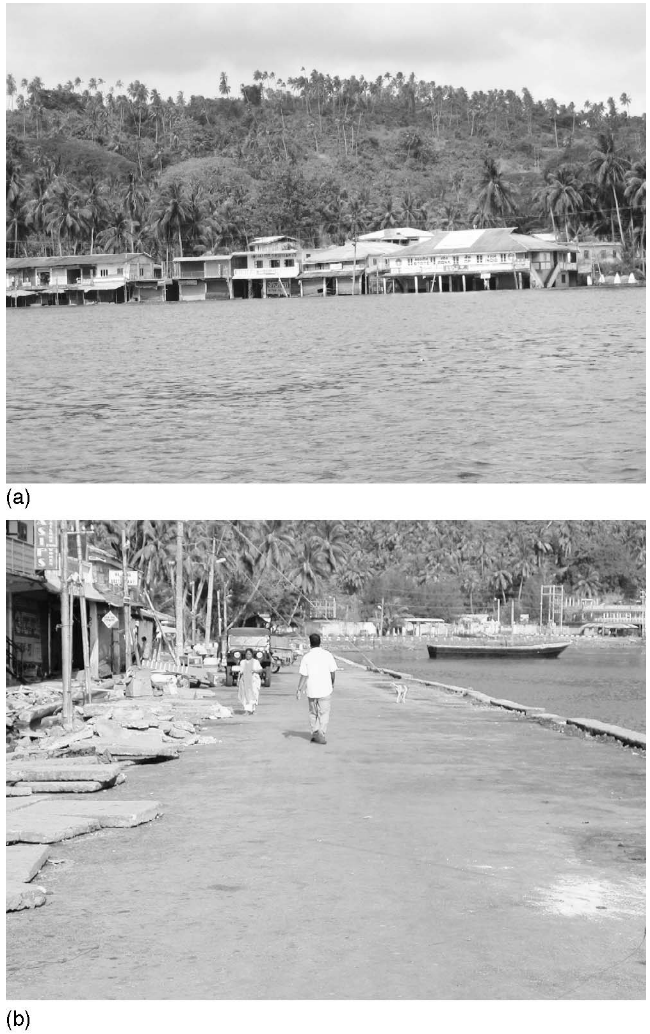


Figure 30. (a) Inundated shops in the Bamboo Flat area near Port Blair (photo: D. Rai), and (b) heavy RC drain covers were displaced from drains by the tsunami (photo: S. Jain).

members such as columns and roof trusses are corroded, and the connections are weakened. The loss of the hospital severely affected the postearthquake care of the survivors on the island.

CONCLUSIONS

Severe shaking-related damage suffered by the recently constructed RC buildings clearly shows that earthquake-resistant design and construction are not being practiced

Figure 31. The old dry dock in the marine jetty dry dock complex was inundated in seawater after the event, and the masonry walls were damaged (photo: H. Kaushik).

in the A&N islands. In addition, the quality of material and construction was found to be quite poor in several privately owned as well as government RC buildings. The mandatory seismic codes are not being used in designing the RC buildings, and therefore ductile detailing was not found in the columns of several recently constructed buildings. On the other hand, the traditional wood houses constructed of locally available timber performed extremely well in response to ground shaking. Also, several old masonry structures on the islands performed well during the earthquake, thus revealing the high quality of masonry construction practice prevalent in India as late as the first half of the twentieth century. During the ground shaking, a large amount of lateral ground spreading, liquefaction, and landsliding occurred at several places on the islands. Repairs undertaken on the islands after the 2002 Diglipur earthquake in North Andaman Island were found to be inadequate, and such buildings sustained damage again in the 2004 event.

Large-scale destruction was observed in the A&N islands after the 26 December 2004 earthquake because of the tsunami. Basic issues of earthquake safety in buildings (such as integral structure with good configuration, basic stiffness, and ductility) were also found to be helpful in resisting the tsunami effects. Coastal regulation zone requirements need to be implemented in the region. Land-use zoning needs to be revised to move critical facilities away from the coast.

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(a)

(b)

Figure 32. A hospital unit at Hut Bay in Little Andaman Island that is several decades old: (a) steel beds were punctured through the asbestos vertical cladding during the tsunami, and (b) collapse of the front portion of the hospital due to ground shaking (photos: C. Murty).

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